Iterative Magnetic/Structural Simulation of a MEMS Micro-shutter

Abed M. Khaskia[a], David J. Power[a], James P. Loughlin[b]

[a]Mallett Technology, Laurel, MD 20707
[b]NASA/Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

A finite element model has been created that simulates the magnetic actuation of a cobalt-iron covered, 0.5µm thick, silicon nitride micro-shutter. The micro-shutter will be used as a transmissible filter in a space-based Multi-object Spectrograph (MOS). A laminated tri-pole permanent magnet is scanned across an array of shutters. The applied magnetic force twists the shutter's torsion hinge and actuates the shutter from the closed, 0 degree, position, to the open, 90 degree position. A sequential analysis method was selected. This method uses the interaction between the magnetic and structural fields and is accomplished via the load vectors. The simulation results are compared to experimental measurements of fabricated micro-shutter devices.

Keywords: MEMS, micro-shutter, silicon nitride, magnetic, sequential analysis

1   Introduction

The James Webb Space Telescope (JWST) is being developed to determine the origin of galaxies. To accomplish this, JWST needs a Multi-object Spectrograph (MOS) for Near Infrared (NIR) observations. In order to reduce the background noise during observation, the MOS must have field selection capabilities. The field selector will eliminate unwanted cosmic observations and leave only the object that the science team wishes to observe. One method being considered for field selection is a transmissive microelectromechanical (MEMS) micro-shutter array.

The micro-shutter array is created by etching a 100µm thick silicon wafer down to an embedded 0.5µm silicon nitride membrane. The silicon nitride is etched away using a deep reactive ion etch (DRIE) procedure. What remains is an 80µm x 90µm shutter with a 90µm x 3µm torsion hinge, Figure 1. The overall dimension of the shutter pixel, including sidewalls, is 100µm x 100µm. Two more layers of aluminum and iron cobalt providing the electric and magnetic properties to the array, are deposited onto the micro-shutters' surface.

Early concepts of the micro-shutter array used electrostatic actuation for opening individual shutter pixels. Electrostatic/structural finite element models were developed to determine the voltage required for actuation. The analysis showed that the actuation voltage required was too high for space applications.
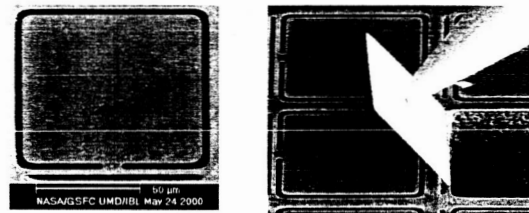

Figure 1: SEM images of the silicon nitride micro-shutter.

A magnetically actuated micro-shutter array is developed as a way to reduce the required operating voltage.

Two thousand angstroms of magnetic material, Fe-Co, is deposited onto the silicon nitride shutter. A laminated permanent tripole magnet scans across the array and creates a strong magnetic field close to the magnet's centerline. The micro-shutters, which originally start closed, unstressed, and horizontal, rotate 90 degrees to the open position. (Fairly high stresses are developed in the torsion hinge on actuation.) Once the shutter is rotated to the open position, a much "low" voltage is applied to the sidewall electrode and the shutter is captured electrostatically in the open position.

The ANSYS/Multiphysics[1] finite element analysis program is used to perform the required coupled field analyses. Electrostatic/structural analysis is performed to determine the voltage required to electrostatically capture and hold the micro-shutter. A sequential, iterative, magnetic/structural analysis is performed to characterize the motion of the magnetically actuated micro-shutter.

2   Sequential Magnetic Analysis

The magneto-structural analysis is a form of two field analysis, namely magnetic and structural fields, and as such it requires models that can be used in both fields with

the highest level of reliability and controlled accuracy. Considering both fields and the micro-shutter geometry, a two-dimensional modeling approach gives reasonable results and provides a working design tool for the Micro-shutter Array. In fact, while the magnetic field model is restricted to two-dimensional, the structural one is hybrid, as it included both two and three-dimensional behaviors.

Two analysis procedures with coupled magnetic and structural domains were tested for the magneto-structural analysis. One involves what is known as direct coupling, where the interaction between the different fields is handled through the elemental finite element matrices. The other procedure is known as sequential method, where the interaction between the different fields is accomplished via the load vectors. While the former procedure is mathematically more rigorous, and is more difficult to converge numerically, the latter is more general as it allows for more than two fields to interact, and is easier to converge. One needs to emphasize that both procedures can handle highly nonlinear applications. More details about the procedure can be found in Reference [1]. Additionally, as the sequential procedure is the successful one, it is reported in this paper, and is described, as applied to the micro-shutter device thoroughly in Section 3.

3   Model Details

Two-dimensional magnetic field analysis is used, and two magnetic finite element models are created. One simulates the magnetic field of the permanent magnet only, while the other simulates the domain around the micro-shutter and very close to it. Both models include the air that surrounds the physical objects. One model, referred to here as the field model contains a planar cross section of the magnet and a region of the air next to it, while the second, known as the submodel, contains the micro-shutter and part of the same air domain from the field model. An illustration of both models is shown in Figures 2 and 3.

As the magnetic field analysis is two-dimensional, the ANSYS® PLANE13 coupled field element type is used to model all domains in all materials. Such an element can be used in a directly or a sequentially coupled field analysis, and it possesses multiple capabilities that are activated and deactivated selectively.   Additionally, the field model contains infinite element, namely INFIN119 in order to simulate field decay at the air domain exterior boundary. Vector formulation is employed by both PLANE13 and INFIN119 for the magnetic field simulation.

The field model simulates the magnetic field generated by the tri-pole magnet. It does not contain a simulation of the micro-shutter, as the micro-shutters are relatively very small and their effect on the magnetic field of the magnet is insignificant. The nonlinear material properties for the tri-pole material are incorporated in the form of a BH curve.
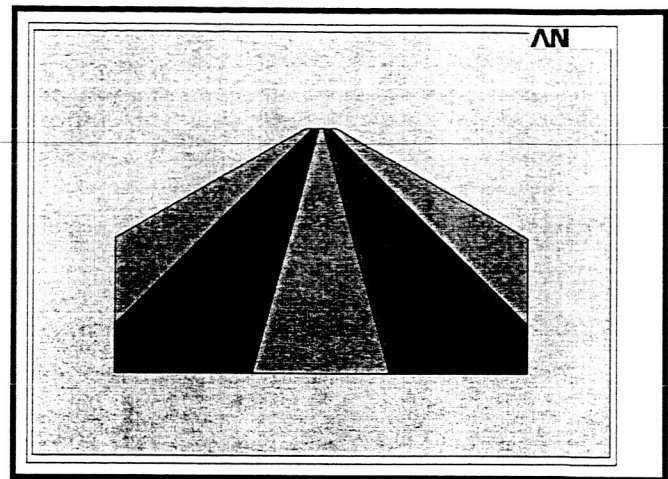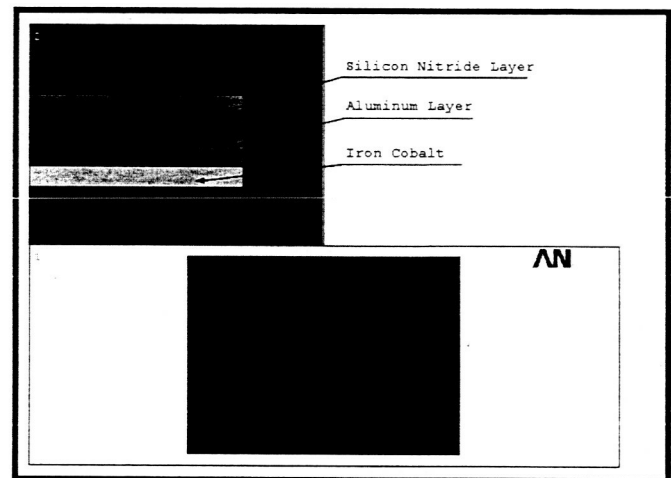

Figure 2, Field Model

Figure 3, Submodel of Micro-shutter

The submodel contains one micro-shutter, with its three layers, and an air domain around them. This air domain is also part of the field model's air domain. Both the silicon nitride and the aluminum are modeled as non-magnetic with air properties, while the iron cobalt is modeled with a nonlinear BH curve. The boundary of the submodel, its location, and other aspects of it, are controlled parametrically in a scripted input file. It is selected such that it does not pass through the magnet geometrical domain. The interaction between the two models is accomplished using the submodeling technique which interpolates the magnetic potential at the submodel boundary nodal points from the field model air domain magnetic potential, and it is based on the nodal points' locations with respect to the field air domain. Such technique is well documented in Reference [1], and has been in use in various finite element analyses types. Figure 4 shows the relative position of the submodel with respect to the field model. An outline of the submodel boundary is shown in red color and is located above the magnet.
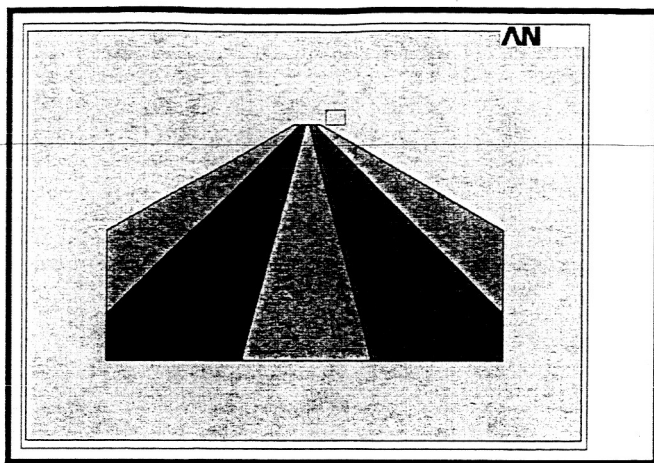
Figure 4, Field Model with an Outline of Submodel Domain

Figure 5, Structural Finite Element Model – 2-D/3-D

The submodel interacts with the structural model of the magneto-structural analysis. Maxwell magnetic forces acting on the iron cobalt and resulting from the magnet are transfer by the sequential process onto the structural model.

The structural model used in the magneto-structural analysis, is a hybrid two and three dimensional one. It simulates a plane strain condition for the micro-shutter main part with all its three layers using the ANSYS® PLANE182 element type, and a three dimensional structural behavior of the tensional bar using BEAM188. This beam is capable of modeling three dimensional geometric and material nonlinear behaviors with general cross sectional properties including variable integration cells. A Special link element type, namely MP184 is used to tie the plane strain part of the model to the three dimensional beam. Figure 5 illustrates the finite element model with the planar and the beam elements. The colors of the planar element indicate the different materials of the micro-shutter layers. The effect of the micro-shutter's neck attaching the actual micro-shutter to the torsion bar is incorporated in the model by shortening the beam length along the z-axis by a value equals to the neck width, which increases the structural model's torsion stiffness.

Only geometric nonlinear behavior, which includes large deflection and stress stiffening effects, are included in the structural model. Therefore, only linear structural material properties are used in the model, and they are consistent with published values, [2], [3] and [4].

All material properties are at room temperature. They can be easily changed by editing the scripted input files to incorporate any other properties; such as material properties at cryogenic temperatures.
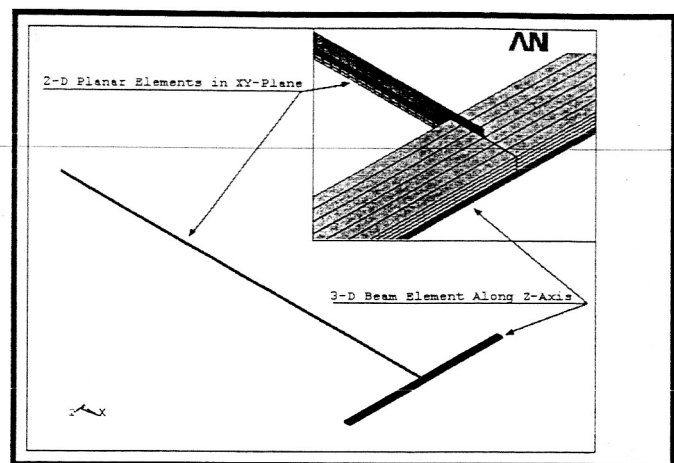
4   Solution Procedure

A sequential solution procedure is used for this analysis. The analyses, both magnetic and structural are static. The solution procedure uses the models described in Section 3; namely the field model and the sequentially coupled submodel and the structural model.

The steps in the actual solution process are:
1. The geometry of micro-shutter is created.
2. The two finite element models, one is the field model and the other is the submodel are created. The models are related in terms of global location. Additionally, the boundary of the submodel air domain is defined such that it can move relative to the tri-pole magnet's position.
3. The field model is solved once using the nonlinear magnetic solution options.
4. An iterative process is initiated which creates two finite elements models from the generic submodel, namely magnetic field and structural models. This process moves the boundary of the magnetic field submodel relative to the magnet and interpolates the values of the magnetic potential at this boundary. It then solves the resulting magnetic field submodel using the nonlinear solver options. The resulting Maxwell forces acting on the iron cobalt layer are retrieved, and then applied to the structural model. Finally, it updates the geometry of the micro-shutter submodel based on the structural solution, using a known morphing and remeshing procedure.
5. The interactive process starts and ends where the micro-shutter is at a user defined starting and ending positions. Clearly the number of interactions depends on the magnet's speed and these positions. The faster the magnet moves, the less iterations are required.

6. In order to maintain dimensional consistency between the magnetic and the structural models of the micro-shutter, the Maxwell forces are multiplied by the width of the micro-shutter.
7. As the solution is nonlinear, its accuracy is controlled by finite element mesh size as models are meshed and by nonlinear convergence criteria in all models as they are solved.
8. The procedure tracks Maxwell forces and micro-shutter position as it rotates with respect to the hinge. The forces are stored in internal database arrays, while the micro-shutter's position is stored in a graphic file.
9. Databases and results files are created for all models and they can be used for various post-processing tasks.

5 Loading and Boundary Conditions

The magnetic field model did not require any boundary conditions since it is bounded by infinite elements capable of modeling magnetic field decay. The magnetic load is provided by the tri-pole permanent magnet.

The magnetic submodel also did not require any boundary conditions other than the magnetic potential values that are obtained from the primary field model through the interpolation scheme of the solution procedure of Section 4.

The structural finite element model required displacement constrains applied on the torsion beam end nodal points and at the node connecting the beam to the planar element through the MPC184 elements. The beam is completely fixed against all translations and rotations at the end nodal points, which simulate fixed support into the side walls of the micro-shutter's well. The beam nodal point connecting it to the planar element is forced to have two-dimensional displacements in the XY-plane, namely the Z translation and the rotations about X and Y-axes were constrained, which simulates the presence of symmetry condition at the micro-shutter neck.

The only forces used in the models are Maxwell forces, which are transferred from the magnetic submodel onto the structural model.

6 Analysis Results

The analysis results for the micro-shutter are studied, and in order to qualify the solution procedure and to compare certain results with those available from NASA, the following data is reported:

1. Maxwell magnetic forces acting on the micro-shutter.

2. Reaction forces and moment at the anchor nodal points of the torsion beam.
3. Rotation angle on the micro-shutter.
4. Von-Mises stress in the micro-shutter when it is at the 90° position as it rotates against the torsion beam.
5. Magnetic field flux density for the field model and the submodel when the micro-shutter is a 90° position.

Figures 6 and 7 show the Maxell forces acting on the micro-shutter as a function of the its position with respect to the magnet's center line, which is measured from the micro-shutter's anchor point or hinge. The forces are in a Cartesian global coordinate system, which is shown in Figure 5, with the lateral forces along the X-axis and the vertical one along the Y-axis. The Figures show a maximum value of about 12.5 uNT for the lateral force and about 22 uNT for the vertical one.
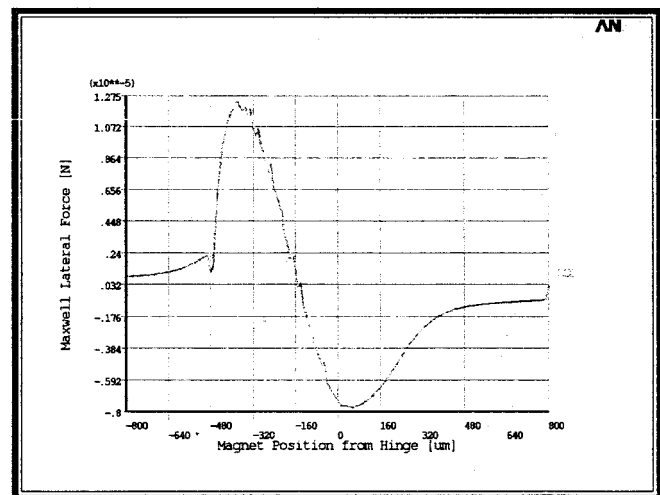
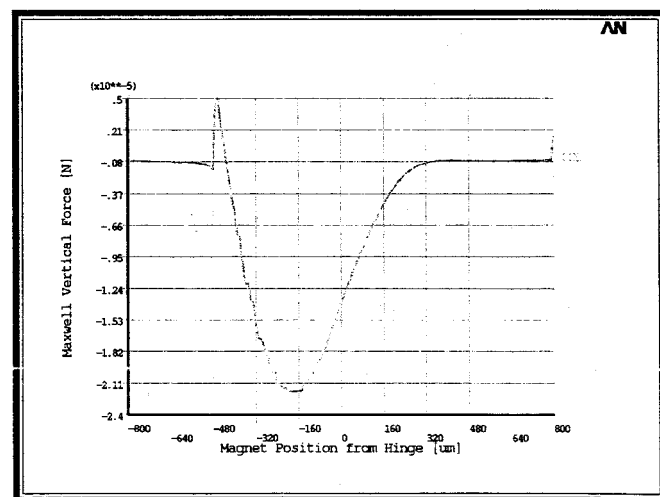**Figure 6, Maxwell Lateral Force [N]**

Figure 7, Maxwell Vertical Force [N]

Figures 8 and 9 contain the total reaction forces at the torsion beam's support location plotted similar to the above figures as a function of micro-shutter position with respect to the magnet. Notice the consistency and agreement between the Maxwell forces of the above figures and the total reaction forces in the lateral and vertical directions. Additionally, each reaction force curve is a reflection of the corresponding Maxwell force curve. Thus the maximum values for the reaction forces are 12.5 and 22 uNT or the lateral and vertical directions respectively.
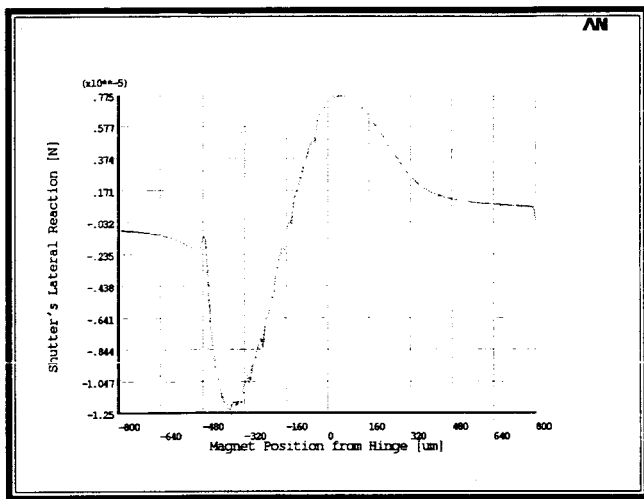
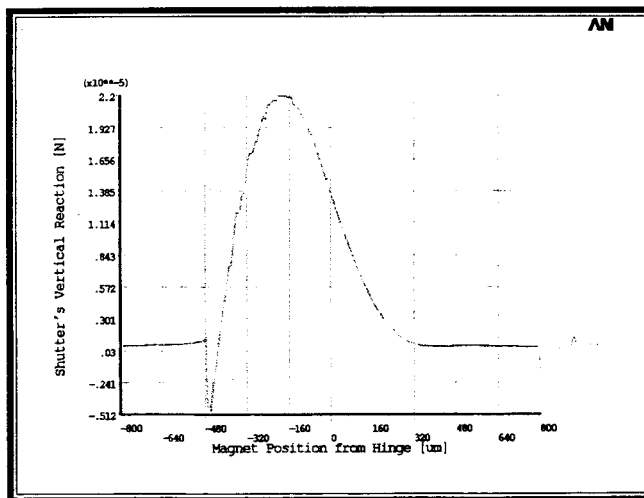**Figure 8, Total Lateral Reaction Force at Hinge [N]**

Figure 9, Total Vertical Reaction Force at Hinge [N]

Similar to the above curve, the curve for the total reaction moment at the beam's support location is shown in Figure 10. It shows a maximum value for this moment of about 2.35E-9 N-m or 2.35E3 uNT-nm.

The micro-shutter rotation angle versus the magnet's relative position is shown in Figure 11. The figure shows that the micro-shutter passes through the 90° wall position, as it is allowed to do so, and since the wall is not actually

modeled. The micro-shutter reached a maximum angle of about 106°.

A plot illustrating the micro-shutter's deformation and Von-Mises stress is shown in Figure 12, and a highlight of the original geometry of the micro-shutter is included in it as well. Notice the large amount of twist experienced by the torsion bar shown in the figure.
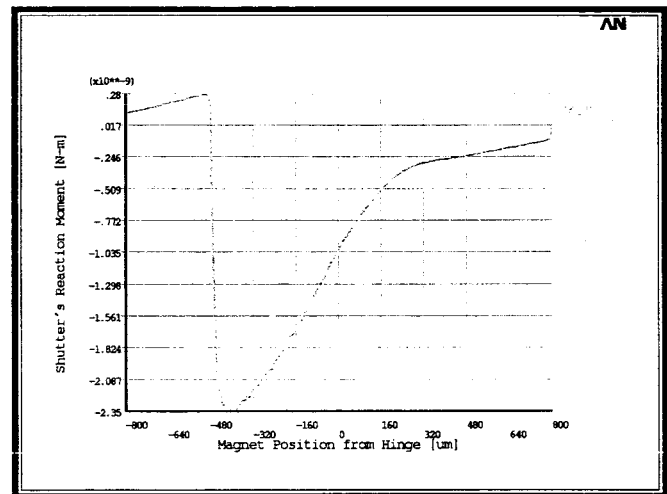

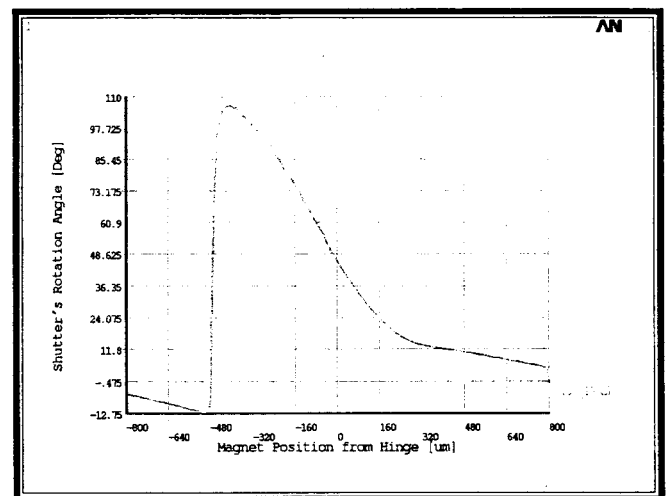**Figure 10, Total Reaction Moment at Hinge [N-m]**

Figure 11, Rotation Angle of Micro-shutter [Degrees]

The flux density of the magnetic field for the global field model and the submodel is shown respectively in Figures 13 and 14 as the micro-shutter passes around the 90° position. The highlight in Figure 13 is for the submodel domain, while that in Figure 14 is for a cross section of the micro-shutter. The figures demonstrate the agreement between both figure with respect to the values of the counters and their shape.

Figure 12, Micro-shutter around 90° Position - Von-Mises Stress and Deformed Shape with Original Geometry

Figure 13, Magnetic Field Flux Density when Micro-shutter around 90° Position – Field Model Results

Figure 14, Magnetic Field Flux Density when Micro-shutter around 90° Position – Submodel Results

7 Conclusions

The primary focus of this project is the development of finite element models and procedures capable of analyzing the magneto-structural behavior of a MEMS micro-shutter. Hybrid two and three dimensional models were created. The mixing of two and three dimensional elements in the same analysis database is found challenging. A significant milestone was reached in stabilizing the solution process in this database.

The application of the submodeling approach to pass magnetic field potential from the global field model to the local magnetic model, which is referenced here as the magneto-structural submodel, is the key for the success of the modeling approach presented.

For solving the magneto-structural analysis two approaches are tried; the directly coupled and the sequentially coupled approached. Although the directly coupled is mathematically more rigorous, it did not converge, and the sequentially coupled approach converged and is found numerically more stable.

The reaction forces and the moment at the hinge of the magneto structural model have maximum values that are consistent with those obtain by NASA's analyst in different analysis [5].

The Maxwell forces calculated in the magnetic model and are shown in Figures 6 and 7 are in agreement in terms of shape and values with the reaction shown in Figure 8 and 9 reaction. Such behaviors indicate numerically converged nonlinear structural solutions.

The reaction forces, reaction moment and the rotation of the micro-shutter shown in Figures 8 through 11, show "numerical noise" which was found more sever in coarser finite element meshes.

The field model used infinite boundary element type, which has, based on the recommendation of Reference [1], special requirement for its orientation with respect to the origin of the finite element model.

All models and procedures created use parametric or almost parametric representation of models geometry and loading sequences and as such they provide good tools for what-if analysis scenarios.

The analytical results correlated extremely closely with the results from micro-shutter arrays magnetically actuated in the lab.

None of the analysis presented addressed any hysteresis magnetic effect, which could be significant for subsequent actuation of the micro-shutter. This could be addressed in a future modeling effort.
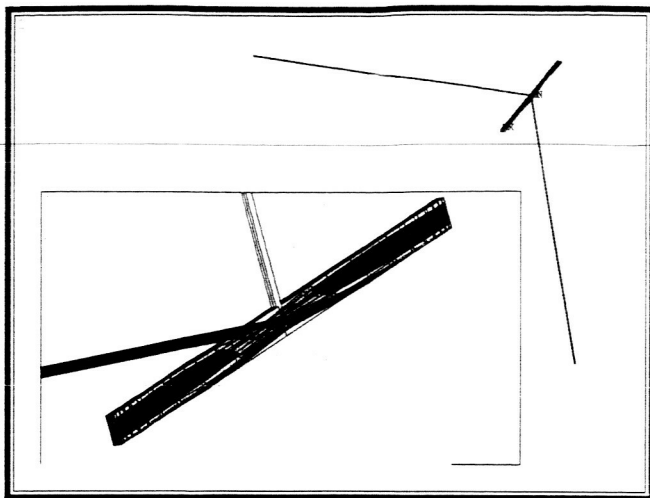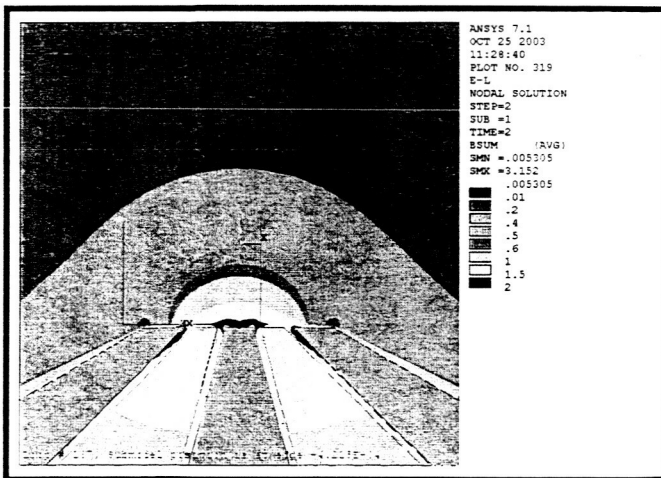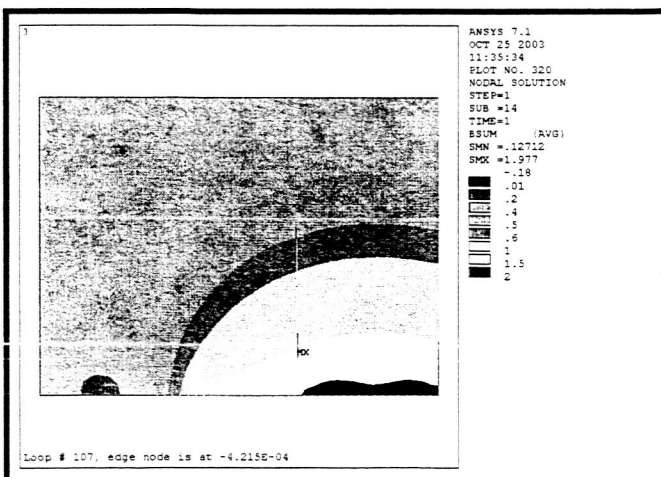
8 Acknowledgments

9 References

[1] ANSYS Corporation, Multiphysics version 7.1, Canonsburg, PA 15317

[2] G. Coles, R. L. Edwards, W. Sharpe, The Johns Hopkins University, Mechanical Properties of Silicon Nitride, SEM Annual Conference, June 4-6, 2001

[3] ASM International, Engineered Materials Handbook, Volume 4, Ceramics and Glasses, p 588-592

[4] Mori, K. "Aluminum Alloy Thin Film Mechanical Test Report", NASA/GSFC, September 13th, 2001.

[5]Loughlin J. P. et al, "Structural Analysis of a Magnetically Actuated Silicon Nitrate Micro-Shutter for Space Applications", 2002 ANSYS Conference, Pittsburgh, PA, May 2002